Community Centre Improvement to Reduce Air Conditioning Peak Demand

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Abstract

Purpose / Context - Many developed countries experience late afternoon or evening electricity peaks. In summer peak demand regions, these peaks are most likely the results of residential air conditioning demand.

Methodology / Approach - This research is to investigate the air conditioning peak demand reduction potential from a variety of building and operational improvement options in a community centre case. Scenarios of increased thermal mass (rammed earth), more efficient glass sliding door options and control methods are simulated.

Results – Building improvement with integrated control performs best at reducing air conditioning peak demand and energy consumption. However, the control method is the most cost effective way of reducing the peak demand.

Key Findings / Implications – The integrated design and operation strategy for the community centre would significantly alleviate the peak demand pressure on electricity network infrastructure and energy so as to lower the carbon footprint onto the environment.

Originality – This study examined a residential community centre case from both design and operation aspects. The simulation is completed in half hourly intervals under real world tariffs.

Keywords - building improvement; thermal mass; operational strategy; air conditioning control; demand side management

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1. Introduction

Electrical performance of residential housing and communities impacts significantly on residents, investors, utilities and society. Peak demand is the most important factor for electricity infrastructure from transmission to distribution to community networks, because high peak demand may lead to excessive heating of conductors and the failure of electricity supply. Australia's electricity peak load is in the evening from 4pm to 9pm (AEMO, 2015) confirming that load from the residential sector has the strongest demand on the electricity network, rather than industrial or commercial loads.

With more sustainability features, such as large amounts of indoor thermal mass in the building structure as well as furnishing (Reddy, Norford, & Kempton, 1991) and better management of heat transfer, sustainable housing can be utilised to store more coolness for longer time periods in regions of summer peak demand, or more warmth for longer time periods in regions of winter peak demand. In essence, sustainable residential buildings could be viewed as thermal energy storage devices. However, it needs investigation to confirm whether adding thermal mass as thermal energy storage will reduce air conditioning (A/C) peak demand in individual cases.

As a form of thermal energy storage (TES), building thermal mass can be used to reduce peak demand (Reddy et al., 1991; Reynders, Nuytten, & Saelens, 2013). In fact, building structure is a large thermal mass for energy storage but its drawback is that its efficiency in terms of energy discharged verses energy charged is low (in the range of 26.47%~41.61% for different weighted buildings (Xue, Wang, Sun, & Xiao, 2014)), compared to electro-chemical batteries' efficiency of 65% to 98% (Christiansen & Murray, 2015). In reality, once the building is designed and constructed, there are no extra costs for using building thermal mass as energy storage.

As a part of operational strategies, demand side management can be used to reduce residential neighbourhood peak demand (Pezeshki, Wolfs, & Ledwich, 2014), improve electricity network reliability (Narimani, Nourbakhsh, Ledwich, & Walker, 2015) and increase household photovoltaic energy local consumption (Liu, Ledwich, & Miller, 2015). When operational strategies are adopted, building thermal mass performs better to reduce peak demand. Where summer peak demands are larger than winter's, pre-cooling using building thermal mass can effectively shave electricity peak demand, maintain comfort levels as well as avoid creating a new peak in a later time (Katipamula & Lu, 2006; Liu, Ledwich, & Miller, 2016; Perez, Baldea, & Edgar, 2016; Xue et al., 2014). Pre-cooling can also potentially reduce the risk of high charges when the electricity price is volatile (Marwan, Ledwich, & Ghosh, 2012). These studies have opened a gate for cross-disciplinary research between mechanical and electrical disciplines; however existing studies often did not consider the real world demand tariff in smaller time intervals of half hour or less and missed the justification for their proposals' implementation cost.

Efficiency improvement measures can reduce peak demand averagely at network scale, e.g. building insulation improvement. Through improvement in roof insulation, A/C peak demand could be reduced on averagely by 14.3% in Australian capital cities according to two simulated houses configurations (Saman et al., 2013). However, whether efficiency improvement would always reduce A/C peak demand of individual cases in hot climates needs further investigation.

To achieve a reasonable outcome considering efficiency, costs, benefits and technology, communities need evaluation of different building improvement options and operational strategies, including demand side management –control of electrical appliances.

This study considers a South East Queensland community centre building with a central A/C as the largest electrical load. The aim of this research is to investigate which building improvement measure, increased indoor thermal mass or improvement in glazing performance characteristics, reduces the A/C half hourly peak demand the most and which strategy is more cost effective. It further aims to determine how integration of these methods with operational strategies could further reduce peak demand.

The methodology is described in Section 2. Section 3 presents the simulation results for the case studies. Section 4 extends the study in the discussion with the combination of improvement in building design, efficiency and operational strategy.

2. Methodology

This section illustrates the methodology to quantify the reduction of half hourly A/C peak demand in a real Queensland community centre with different building improvement measures. The electricity demand tariff in Queensland is based on the highest half hour electricity consumption in a month. For the community case, the rates are $31.1025AUD per kilowatt (kW) for peak demand and $0.1192AUD per kilowatt hour (kWh) for energy (Queensland Competition Authority, 2015). The onsite meter records the highest half hourly electricity consumption. If the immediate past half hour recording is higher, the recorder will be updated. Site energy auditing identified that the community centre air conditioner is the largest load. This study is focused on how to reduce peak demand from the air conditioner in half hourly intervals.

Table 1: Building and Air Conditioner Parameters

No.	Description	Value	Unit
1	Heat Transfer Coefficient (HTC) Eastern Wall	3.0446	$W/m^2 \cdot K$
2	HTC Southern Wall	2.6394	$W/m^2 \cdot K$
3	HTC Western Wall	1.9027	$W/m^2 \cdot K$
4	HTC from Northern Wall	1.0331	$W/m^2 \cdot K$
5	HTC Ceiling	0.667	$W/m^2 \cdot K$
6	Eastern Wall Area	77.32	m^2
7	Southern Wall Area	45.59	m^2
8	Western Wall Area	50.4	m^2
9	Northern Wall Area	53.4	m^2
10	Ceiling Area	356.85	m^2
11	Indoor Thermal Mass	5.95	MJ/K
12	Air conditioner input power (cooling)	14	kW
13	Energy Efficiency Ratio (Cooling)	2.5	
14	Desired Temperature Band	24~26	°C
15	Simulation Initial Temperature	25	°C
16	Outdoor Temperature	34	°C

From site energy auditing and computer modelling (regulatory accredited software BERS Pro), the building, air conditioner and simulation parameters are listed in Table 1. These parameters are used in MATLAB environment to simulate the central air conditioning operation and indoor temperature with state space models (Liu et al., 2016). The main structure of the building is concrete, however there are large areas of glazing. 21% of the external wall area consists of energy inefficient single glazed sliding doors, providing an option to consider more energy efficienct glazing for better energy saving and better financial performance over the long term. The heat transfer coefficient through the concrete floor is neglected because of relatively high ground temperature (over 17°C all year) and the insulation effect of floor covering, minising heat loss throught the floor.

This building is mainly used for community residents for morning tea, lunch, meetings and other functions. The scope of the simulation is one zone only - the main hall. Other parts of the building (e.g. kitchen and offices) are not conditioned by the same air conditioner nor connected directly to the main hall. The purpose of the modelling is to simulate the reduction of peak demand. The electricity demand of air conditioning is at its maximum at high temperatures, therefore the 90th percentile maximum temperature (34°C) is selected for the modelling (Bureau of Meteorology, 2016).

Peak demand always occurs in one half hour. Based on 38 months of site data, 82% of the site monthly peak demands occurred between 4:30pm to 6:30pm when there is no significant indoor metabolic heat load or solar radiation. Site energy auditing identified that the indoor heat loads in the peak time are from lighting and appliances at idle so the simulation considered indoor heat loads constant at 8327.1W.

The following equation is used to calculate Indoor temperature (T_{in}).

$$T_{in}(k+1)=\Delta Tac(k)+\Delta Tbe(k)+\Delta Thl(k) \quad (1)$$

ΔTac: temperature change due to A/C work
ΔTbe: temperature change due to heat transfer through building envelope
ΔThl: temperature change due to indoor heat loads

Scenario 0 is the base scenario representing the current situation on site. It will build the baseline for comparison with other scenarios.

Scenario 1 is to examine if a certain level of increased building indoor thermal mass would reduce A/C half hourly peak demand. Thermal mass options include rammed earth, concrete, concrete blocks, bricks or water. For this community centre, prefabricated 300mm thickness rammed earth blocks are selected because of aesthetics, easy maintenance, indoor space limitations and specific heat capacity. These rammed earth blocks are \$375AUD/ m^2 with a thermal mass of 1673 $kJ/m^3.K$ (Reardon, McGee, & Milne, 2013). Considering minimum purchasing requirements and budget limitations, the limit for purchasing the rammed earth is from 2 to $30m^2$. This limit is included in the MATLAB Particle Swarm Optimisation algorithm (PSO) (Kennedy & Eberhart, 1995) to identify the optimal thermal mass increase for A/C peak demand reduction. The optimisation objective function is the maximum A/C half-hourly demand reduction.

Because large areas of the external walls are glass, from an efficiency point of view, Scenario 2 is to improve the glass thermal performance (U values $W/\ m^2\cdot K$) through evaluation of various glass sliding door options. Solar heat gain is not an important factor in selecting glass types for this building because of long eaves on the building exterior providing excellent east and west shading and electricity monthly peak demand mostly occurring between 4:30pm and 6:30pm when solar radiation is not strong. Therefore U values of the glass sliding doors are considered to be the selection criteria. Figure 1 presents the candidate glass sliding door unit costs (\$AUD per m^2) against their corresponding U values (watt per m^2 per Kelvin). Glass sliding door products are often custom made and quoted. The pricing used in Figure 1 includes glass, frame, flyscreens and features to match with exsting configuration for the purposes of reducing the community centre building envelope heat transfer, not improvement in solar heat gain, aesthetics or structure.

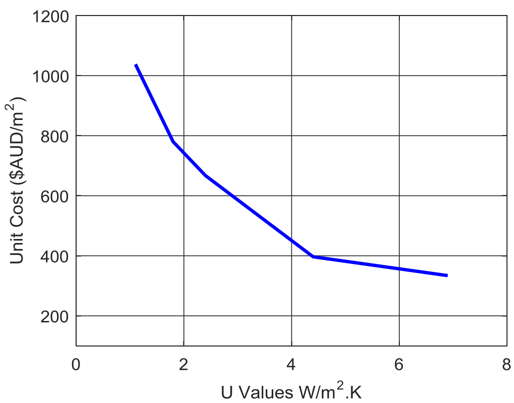

Figure 1 Glass Sliding Door Unit Cost vs U Values

Scenarios 0, 1 and 2 have standard thermostat controlled central A/C. In these scenarios, the A/C works in warming up and cooling down cycles. A consistent initial temperature of 25°C has been used for these scenarios.

Scenario 3 is to examine if operational improvement, i.e. different operational strategies can reduce the A/C peak demand for the community centre. The operational strategies include pre-cooling to the lower band of the temperature range and increasing the thermostat setting by 1°C or 2°C. Higher thermostat settings are not considered due to occupant thermal comfort requirements.

Lastly, the integrated approaches of increased thermal mass, improved glazing and operational strategies are simulated to examine if the combination of these strategies would reduce peak demand and energy consumption further.

3. Results

This section presents the case study results from simulating the A/C operation in the MATLAB environment. Based on site data, 93% of daily peaks happened during 15:30 to 20:30. Therefore, a 5-hour simulation period is chosen to cover the length of possible peak timing.

3.1 Scenario 0 – Base Scenario without any improvement

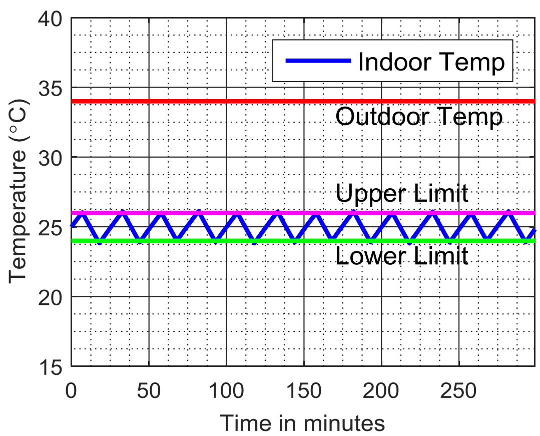

Figure 2 Base Scenario Indoor Temperature

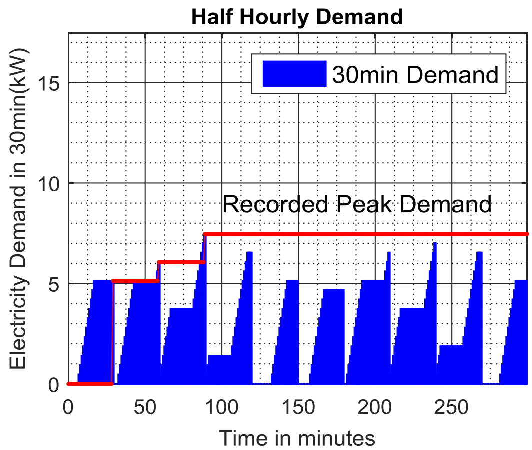

Figure 3 Base Scenario Half Hourly Demand Recorder

Figre 2 represents the base scenario without any building improvement. There are 12 operating cycles. Figure 3 shows the peak demand is 7.4667kW from the 3rd 30min interval. This reading is the largest 30min electricity demand in the simulation horizon. The triangular shapes are the demand reading in each 30min. The peak demand is updated every time after 30min if the immediate past 30min has a higher reading. Electricity consumption in this scenario is 30.1kWh. Based on the community case electricity tariff (Queensland Competition Authority, 2015), the total cost of demand and energy for this time period is $235.82AUD.

3.2 Scenario 1 – Increase Building Thermal Mass

Iterations of the PSO algorithm determined that 2.5m^2 of 300mm thick rammed earth needs to be added to the existing building to provide the optimal thermal mass to reduce peak demand. Thermal mass increase beyond this value or less than this value will not reduce the A/C peak demand more than the 2.5 m^2 optimal increase. Figure 4 below presents the indoor temperature profile of the community centre with the optimal indoor thermal mass to reduce A/C peak demand. This scenario has less operation cycles (10 cycles) compared to the base scenario (12 cycles). This added thermal mass would be able to reduce peak demand by 1.4kW however this scenario would consume slightly more energy (30.3kWh) compared to the base scenario (30.1kWh) mainly due to the cooling of more thermal mass.

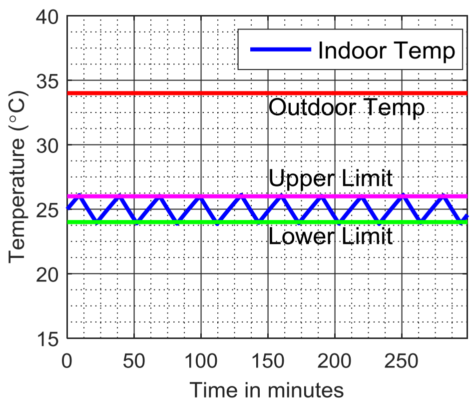

Figure 4 Scenario 1 Indoor Temperature

3.3 Scenario 2 – Improve Glass Sliding Door

Figure 5 presents the peak demand reduction compared with the cost of different glazing options. Higher glazing costs do not guarantee more peak demand reduction because there is no difference in the number of air conditioner working cycles within the same timeframe. For this same reason, when there is no significant difference in U values, the energy consumed by the A/C in the simulation period may be the same. This phenomenon is shown in Table 2 improvement options for glazing with U values of 1.1 to 2.4. Results of evaluating various glazing options are listed in Table 2.

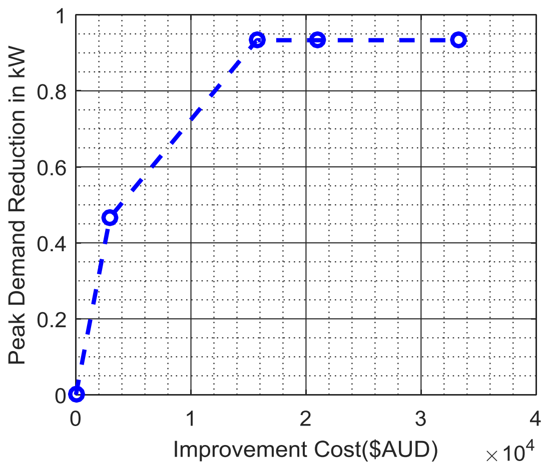

Figure 5 Scenario 2 Peak Demand Reduction vs Cost

Table 2: Scenario 2 Cost and Benefit Analysis of Glass Sliding Door Options

Options	U Values ($W/m^2.K$)	Energy Consumed (kWh)	Air Conditioner Peak Demand (kW)	Peak Demand Reduction (kW)	Improvement Cost ($AUD)	Ratio of Peak Demand Reduction to Improvement Cost
Base Scenario	6.9	30.1	7.4667	N.A.	0	N.A.
Improved Scenario	4.4	28	7	0.4667	2576	**0.00018**
	2.4	25.6667	6.5333	0.9334	13679	0.00007
	1.8	25.4333	6.5333	0.9334	18307	0.00005
	1.1	25.4333	6.5333	0.9334	28892	0.00003

On the last column of Table 2, the ratio of peak demand reduction to improvement cost is used as the performance indicator. The larger the indicator value is, the better the performance. The best performing ratio is highlighted in bold. Glazing with 4.4 U value is the best option in this scenario.

3.4 Scenario 3 – Operational Improvement to Include Operational Strategies

Previous literature (Katipamula & Lu, 2006; Xue et al., 2014) has demonstrated that pre-cooling thermal mass can be used to alleviate peak demand. However, for this community centre case, simple pre-cooling will not reduce peak demand as shown in Table 3 (initial pre-cooling at 23 or 24°C), because the precooling effect wears out quickly in the first half hour of the five hour simulation duration. The same performance indicator is used, showing increase of the temperature band by 2°C is the best option (Table 3).

Table 3: Scenario 3 Options

Options	Strategy	Energy Consumed (kWh)	Air Conditioner Peak Demand (kW)	Peak Demand Reduction (kW)	Improvement Cost ($AUD)	Ratio of Peak Demand Reduction to Cost
Base Scenario	Normal cyclic operation	30.1	7.4667	N.A.	0	N.A.
Operational Strategies	Pre-cooling, Initial at 24°C	30.1	7.4667	0	200	0
	Pre-cooling, Initial at 23°C	28.9333	7.4667	0	200	0
	Uplift Temp. Band by 1°C, Initial at 25°C	28	7.4667	0	300	0
	Uplift Temp. Band by 2°C, Initial at 25°C	25.6667	6.5333	0.9334	300	**0.0031**

4. Discussion

The best performing options of Scenario 1, 2 and 3 are listed in Table 4. The integrated scenarios are further presented in the last three rows. The bold numbers are the best performing in respective columns.

Table 4: Best Performing Options and Integrated Scenarios

Scenario	Description	Energy Saving (kWh)	Peak Demand Reduction (kW)	Electricity Charge ($AUD)	Improvement Cost ($AUD)	Ratio of Charge Reduction to Cost
0	Base Case	N.A.	N.A.	235.82	N.A.	N.A.
1	Increase Thermal Mass	-0.2	1.4	192.3042	938	0.0464
2	Improve Glass Sliding Door	2.1	0.4667	221.0551	2576	0.0057
3	Uplift Temp Band by 2°C	4.4333	0.9334	206.2625	300	**0.0985**
4.1	Integrate the above 1 & 3	4.9	**1.8667**	177.1778	1238	0.0474
4.2	Integrate the above 2 & 3	**5.3667**	1.4001	191.6367	2876	0.0154
4.3	Integrate the above 1 to 3	**5.3667**	**1.8667**	**177.1222**	3813	0.0154

In Scenario 1, the optimal indoor thermal mass increase is 1254.75kJ/K which is 21% increase to the existing thermal mass. It can reduce peak demand by 1.4kW but results in slightly higher energy consumption than the base Scenario 0 due to the cooling of additional thermal mass. In Queensland Australia, demand is measured in half hour intervals. If demand is measured in longer intervals (e.g. hourly) or the building has poor thermal performance, increasing indoor thermal mass may reduce the A/C peak demand more because more thermal mass may be able to reduce the number of cooling down-warming up cycles in the longer interval, reducing the demand measurement.

Scenario 2 performs last in peak demand reduction and second last in the energy reduction. It is not a particularly successful option due to its high cost. This option can still be viable if this cost barrier could be removed. For example, the high glazing cost in Australia may not exist in other countries due to market size, population, competition and distance to manufacturers. It may also be possible to retrofit low-e film to the existing glazing to achieve similar U value improvement at a reduced cost, changing the charge reduction to cost ratio.

Scenario 3 shows that pre-cooling alone does not reduce A/C peak demand or result in financial savings in the half hourly demand charge case. From an investment point of view, uplifting the temperature band by 2°C in Scenario 3 is the overall best option when the ratio of electricity charge reduction to improvement cost is considered as the performance indicator. When design improvements and operational strategy are combined, Scenario 4.3 performed the best in energy saving, peak demand reduction and electricity charge reduction however, its ratio of charge reduction to improvement is not high.

The limitation of this research is that it has not included life cycle cost benefit analysis, battery energy storage or other efficiency measures (e.g. efficiency of appliances, ceiling and roof insulation). Peak demand and energy consumption could be reduced further if battery energy storage and other building and appliance efficiency measures are employed.

5. Conclusion

This research investigated the half hourly peak demand reduction potentials under real world tariffs with a variety of building and operational improvement scenarios. The time interval of half hour is smaller than most of the existing literature. Results show that most of the scenarios would reduce energy consumption; however not all the discussed efficiency measures would reduce A/C peak demand. The most cost effective option considered is the operational improvement by uplifting the A/C temperature band. However, the integrated approach of design improvement and incorporating operational strategy performed best at reducing peak demand and energy usage. The reduced peak demand and energy usage would directly mean less carbon footprint to the environment. Future work includes developing intelligent operational strategies to manage electricity demand with batteries and optimising community electrical infrastructure.

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